Advanced Skutterudite-based Unicouples for A Potential Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG)

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ICT 2017
Pasadena, CA
July 31st, 2017

Agenda

- **Introduction**
  - What is being "enhanced" in the potential *eMMRTG*?
- **Overview of the Skutterudite Technology Maturation (STM or Tech Mat) program**
  - Develop advanced skutterudite (SKD)-based couples for the proposed *eMMRTG*
- **Status of SKD-based couple development**
  - Thermoelectric (TE) material production
  - TE couple fabrication
- **Summary**

What is being enhanced in the potential *eMMRTG*?

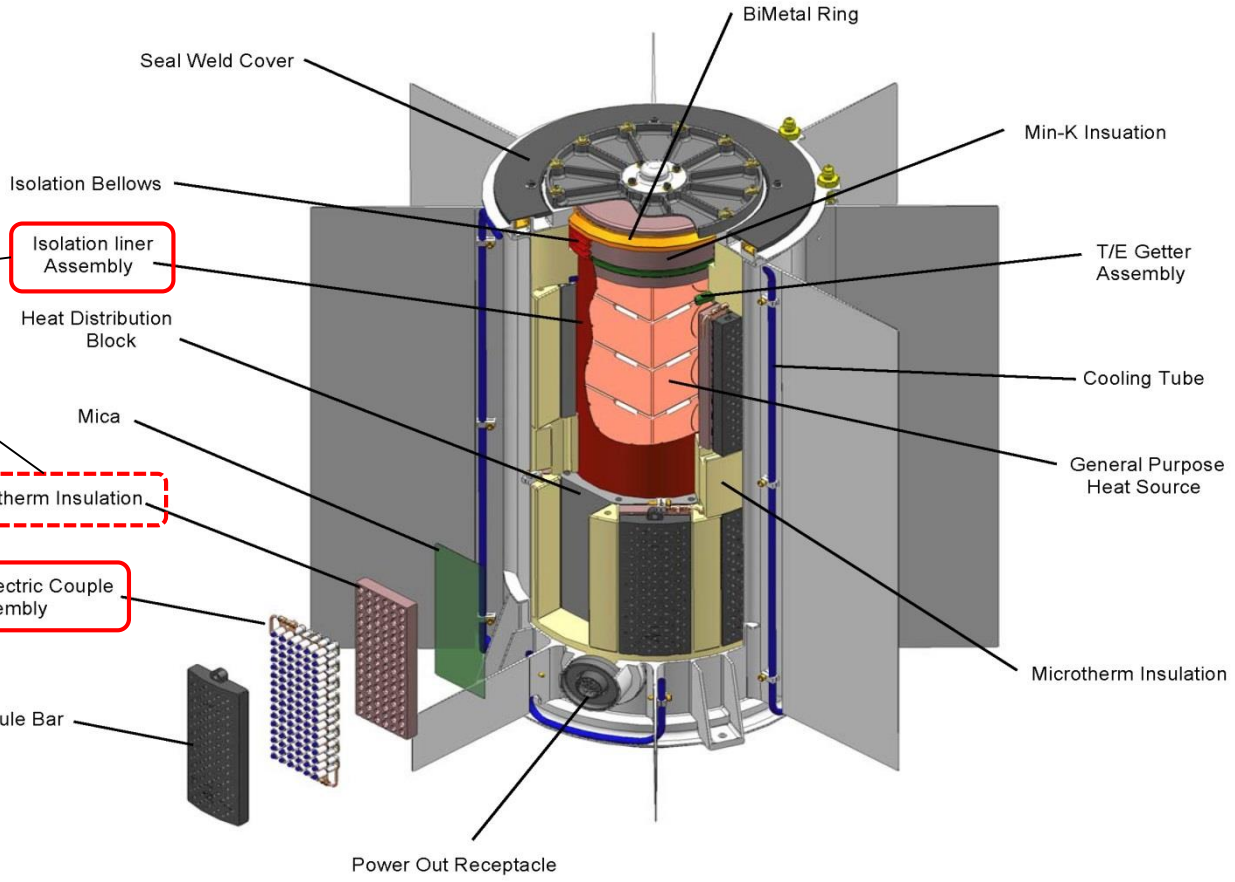
Enhancements under consideration

Known enhancements

Engineering: emissivity change to liner, substitute part of insulation

Changes needed to MMRTG

New Technology: Substitute SKD TECs



Replacing MMRTG couples with new SKD TE couples without significant design changes to the generator

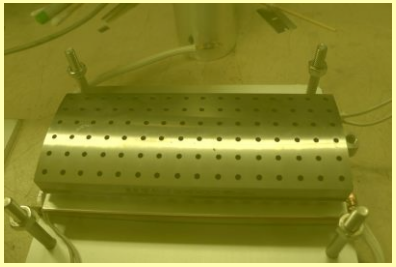
- SKD couples retrofit in the MMRTG TE module (no change in number of couples)
- Simple emissivity change to heat source liner surface will enable use of MMRTG end insulation system
- Volume, mass, and external interfaces remain unchanged
- MMRTG's Multi-mission capability preserved while offering enhancement in power
- Upgraded TE module insulation to suppress SKD material sublimation in progress

A Boost in Conversion Efficiency with Low Risk Enhancements

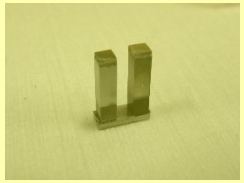
Technology Transfer and Maturation + MMRTG Design Modifications = eMMRTG

Advanced SKD materials with higher performance and higher maximum operating temperature than MMRTG TE materials

Skutterudite (SKD) materials



Advanced SKD eMMRTG modules



SKD couples

10% increase in conversion efficiency over MMRTG couples

Operating temperature rises from 800K to 873K

Liner cross-section change boosts operating temperature

The potential eMMRTG

14% increase in conversion efficiency over MMRTG couples

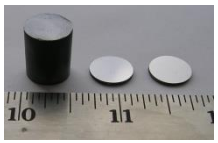
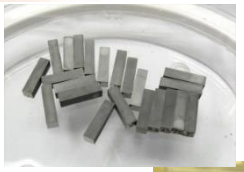
24% increase in conversion efficiency over MMRTG at BOL

Phased Skutterudite Technology Maturation (STM) Program

- **Phase A key accomplishments**
  - Transferred JPL developed TE materials, metallized elements and TE module insulation production procedures to TESI
  - Demonstrated manufacturability and validated performance for SKD materials and elements
  - **Demonstrated manufacturability and performance for 1st iteration SKD couples**
  - **Assessed thermal insulation options for modules**
  - **Initiated life assessment of SKD materials**, coupons, couples

Successfully Passed Gate 1
Oct 2015

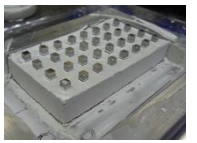
Phase A
~ 2 years

- **Phase B key objectives**
  - Finalize couple design and module insulation/sublimation suppression at the end of Phase B couple development
  - Further establish lifetime performance database through SKD materials, coupons, couples, and modules under nominal and accelerated testing conditions

Gate 2

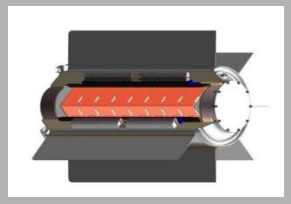
Phase B



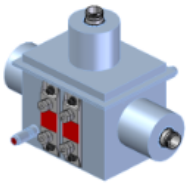
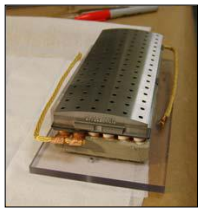
- **Phase C key objectives**
  - Design and demonstrate manufacturability and initial performance for SKD 48-couples modules
  - Finalize a lifetime performance database through SKD materials, coupons, couples, and modules under nominal and accelerated testing conditions
  - Develop a high reliability lifetime performance prediction (LPP)
  - Initiate verification of LPP through 48-couple module testing under nominal and accelerated testing conditions

Gate 3

Potential eMMRTG flight program development (DOE)



eMMRTG

STM Team

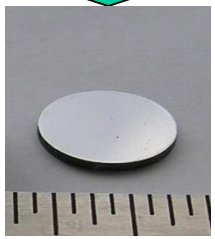
- JPL (Lead), NASA/GRC (support), DOE (Guidance)
- Subcontractors: Teledyne Energy Systems Inc. (TESI), UDRI, ATA

SKD Thermoelectric Material Synthesis (JPL and TESI)

Raw materials

Ball milling

Powder

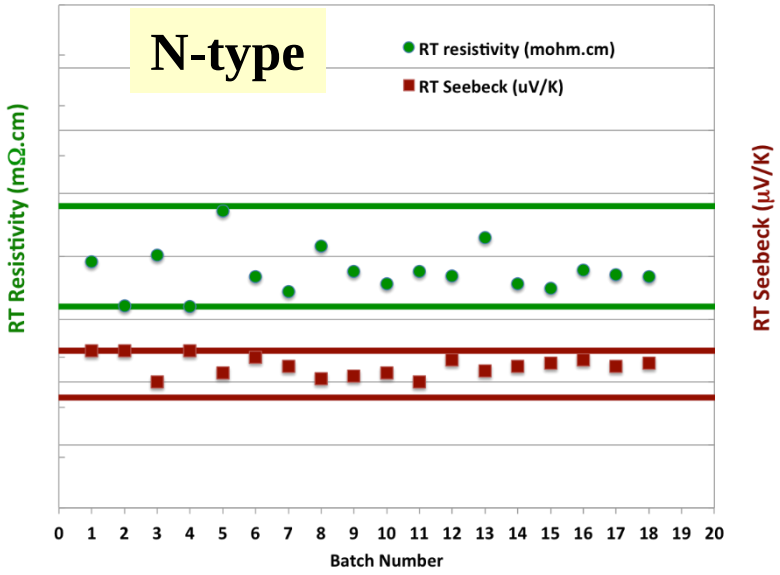


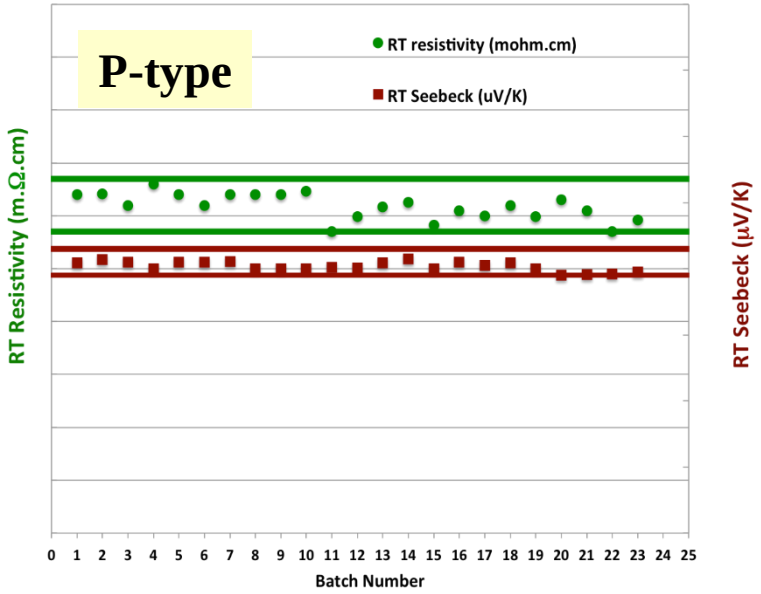
QA puck

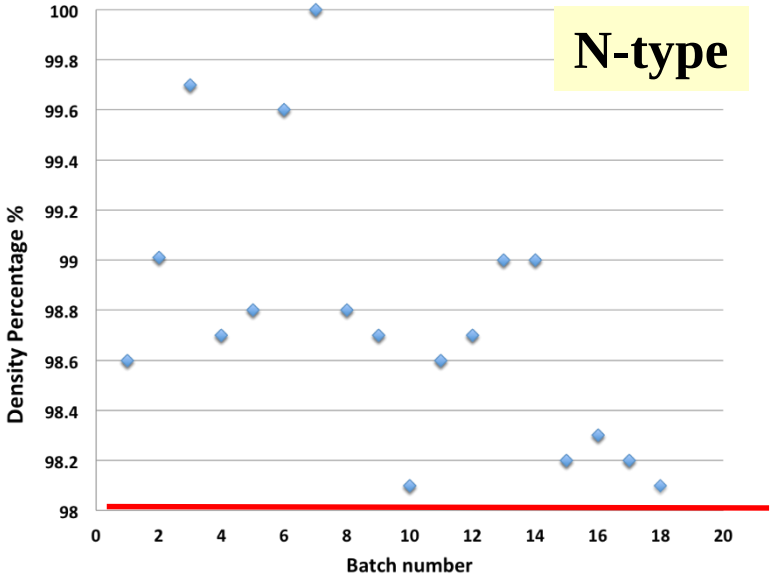
- JPL's procedures for the synthesis of SKD materials transferred to TESI
- Equipment and procedures for the synthesis of p- and n-SKD TE materials established at TESI
- Batch and yield to date sufficient to support the fabrication of a generator
- Performance of TE materials produced by TESI independently verified by JPL and ORNL

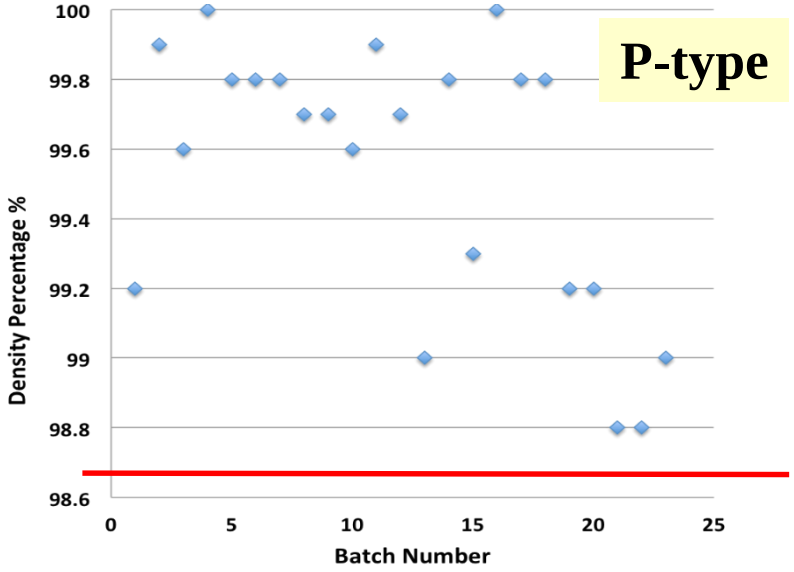
SKD TE materials manufacturing capabilities successfully established at TESI

Room Temperature SKD Thermoelectric Properties (JPL)

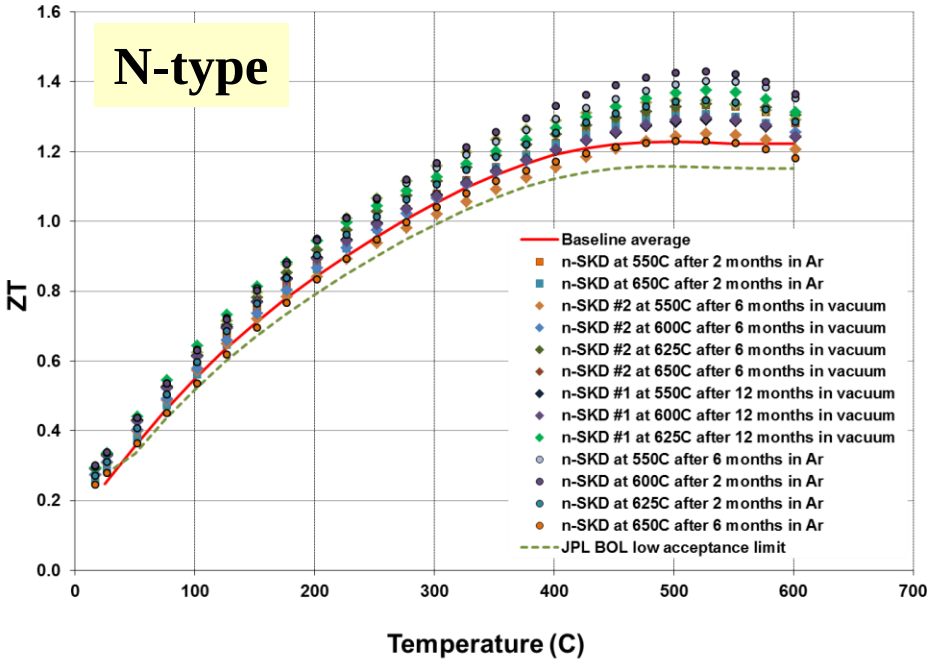


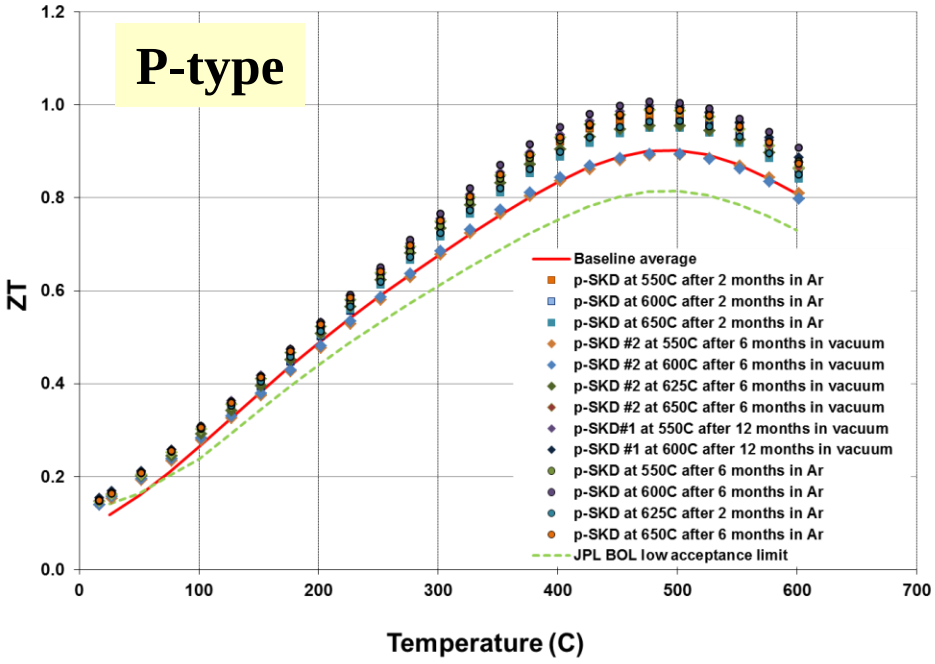






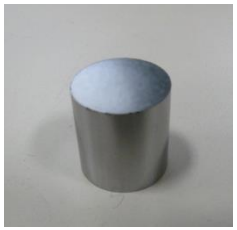
TE Properties Life Testing - Skutterudite in Ar and Vacuum (JPL)





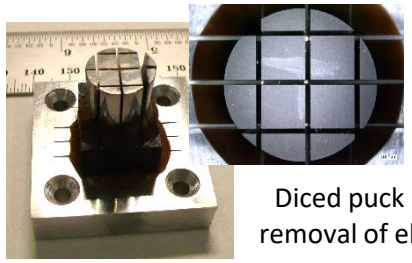
- TE properties of n- and p-skutterudite show no change after 52 weeks of aging in vacuum up to 650C
- TE properties of n- and p-skutterudite show no change after 26 weeks of aging in Ar up to 650C

Development of Low Electrical Contact Resistance (ECR) Metallization (JPL and TESI)



Metallized puck

Dicing saw



Diced puck before removal of elements

Diced elements

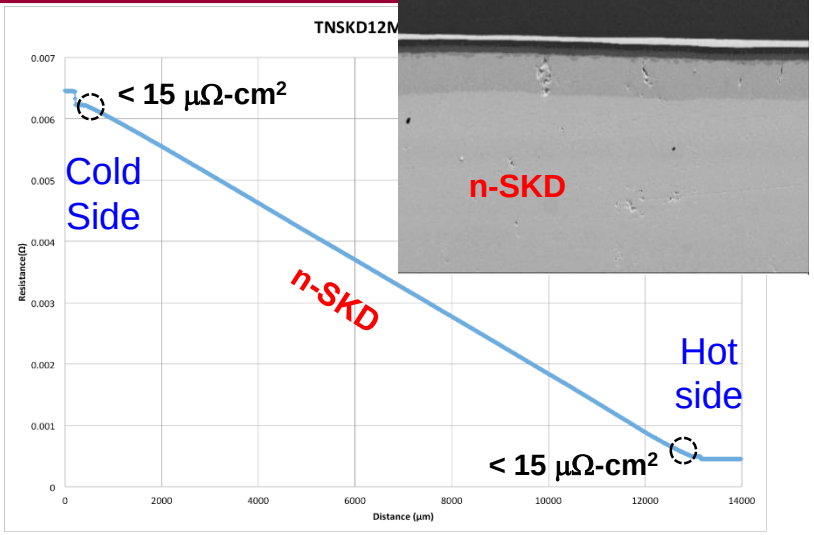
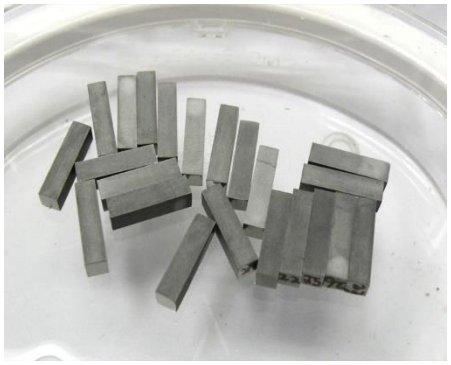
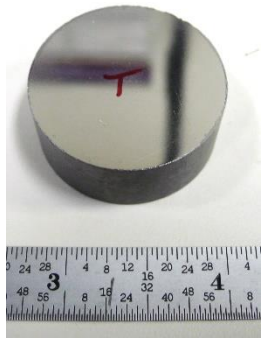


Illustration of a typical ECR scan





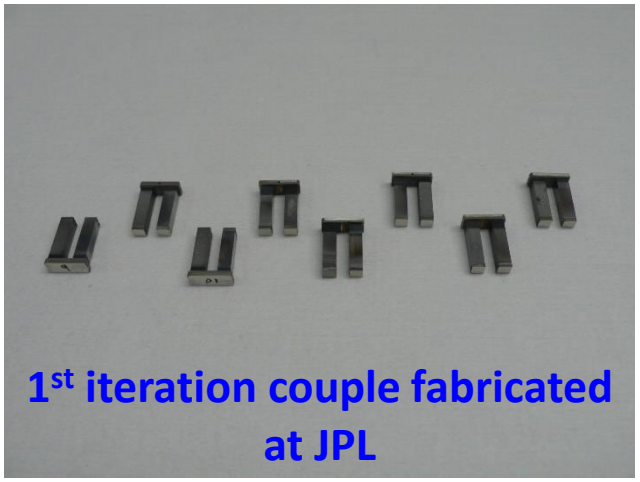
- JPL's procedures for the fabrication of 1st iteration SKD elements transferred to TESI
- Performance of TESI elements verified by JPL

- **Fabricated and cut several n- and p-SKD metallized pucks**
- **Machined SKD legs have low measured electrical contact resistance (ECR) (< 15 μΩ–cm²)**

1st iteration SKD metallized elements manufacturing capabilities successfully established at TESI

Phase A 1st Iteration SKD Couple Fabrication (JPL and TESI)

- JPL's procedures for the fabrication of 1st iteration SKD couples transferred to TESI
- Equipment and procedures for the fabrication of SKD couples established at TESI
- Performance of 1st iteration couples verified by JPL



1st iteration couple fabricated at JPL

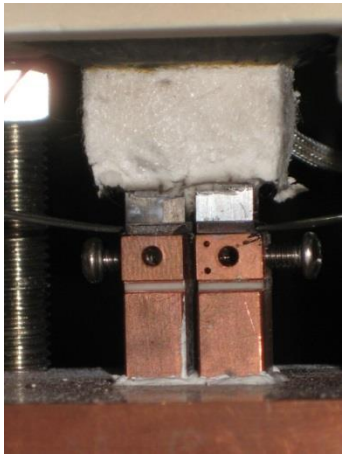
1st iteration couple fabricated at TESI

1st iteration SKD couples manufacturing capabilities successfully established at TESI

Phase A 1st iteration SKD Couple Testing (JPL and TESI)

- **1st iteration couples in vacuum**
  - Four couples tested for 9888 hrs (~1.1 year) at Th up to 625C
  - Encapsulated in insulation (ambiently dried aerogel)
  - Primarily for sublimation suppression

Couple ID	Test duration	Hot-junction T	Cold-junction T
SKD 6 V2	9888 hrs	550 C	200C
SKD 7 V2	9888 hrs	600 C	200C
SKD 9 V2	9888 hrs	600 C	200C
SKD 5 V2	9888 hrs	625 C	200C

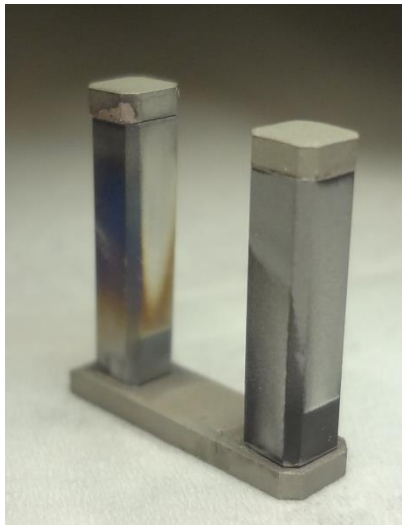


SKD couple tested for 9888 hours at T_h = 600°C and T_c = 200°C

- **1st iteration couples in Ar**
  - Couples typically showed an increased degradation rate compared to vacuum testing
  - Observed degradation associated with oxidation of specific layers in the couple metallization stack
  - Residual moisture/oxygen present in the test chambers and also anticipated at some level in the final generator
  - 2nd iteration couples addressed this sensitivity

2nd Iteration SKD Couple Fabrication (JPL and TESI) – Retired Oxidation Concern

2nd iteration couple fabricated at JPL



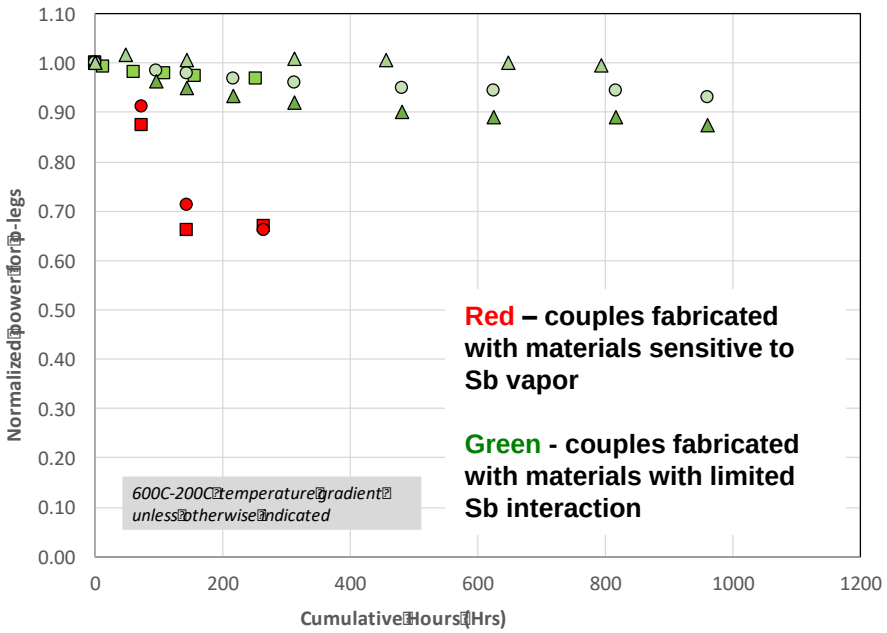
2nd iteration couple fabricated at TESI

- JPL's procedures for the fabrication of 2nd iteration SKD couples with alternate metallization stack (good oxidation resilience) transferred to TESI
- TESI can procure, process, and bond couples with an alternate (good oxidation resilience) metallization layer
- JPL and TESI's couple testing results for 2nd iteration SKD couples showed significantly reduced risk in oxidation concern

2nd iteration SKD couples manufacturing capabilities successfully established at TESI

2nd Iteration Couple Testing (JPL and TESI)

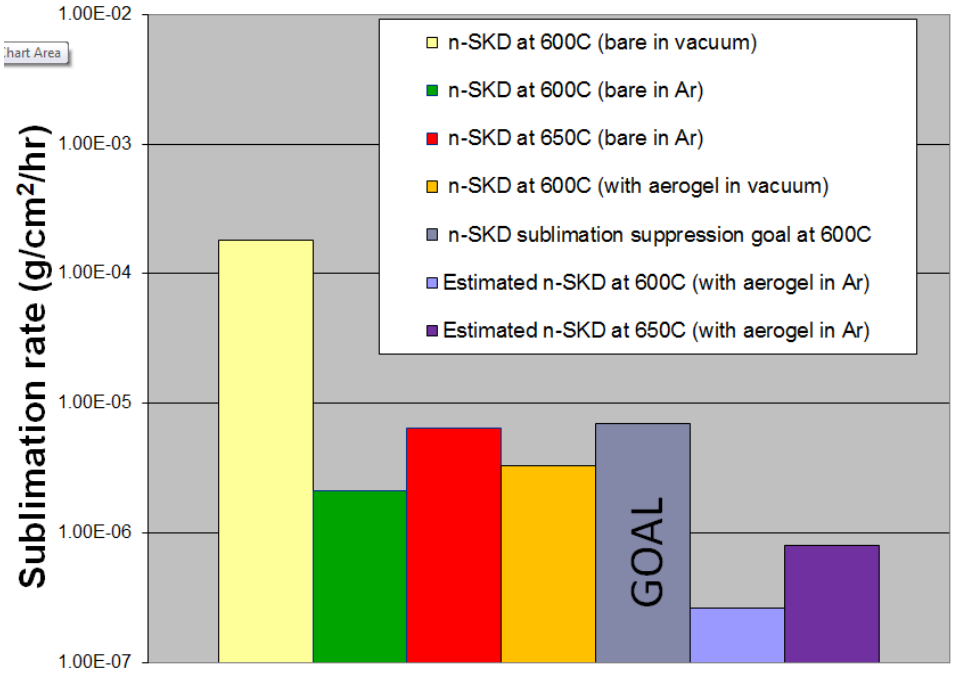
- **Initial 2nd iteration couple testing showed the oxidation concern was retired but specific material layers in the couple were sensitive to Antimony interaction**
  - Antimony reacted with materials/metals in the couple metallization stack (typically in p-leg), forming low melting point (600 – 650C), high vapor pressure compounds
  - Observed couple power degradation due to Sb interaction
  - Antimony vapor was produced by sublimation of SKD materials
- **Initial 2nd iteration couple (Gen. II) testing showed the Sb interaction concern was retired but specific material layers in the couple were degraded by certain diffusion mechanism**
- **Fabrication of 2nd iteration couple (Gen. III) SKD couples using smart materials/metals is in progress (refer to poster titled "Advanced Skutterudite-Based Unicouples for a Proposed Enhanced Multi-Mission Radioisotope Thermoelectric Generator: An Update")**

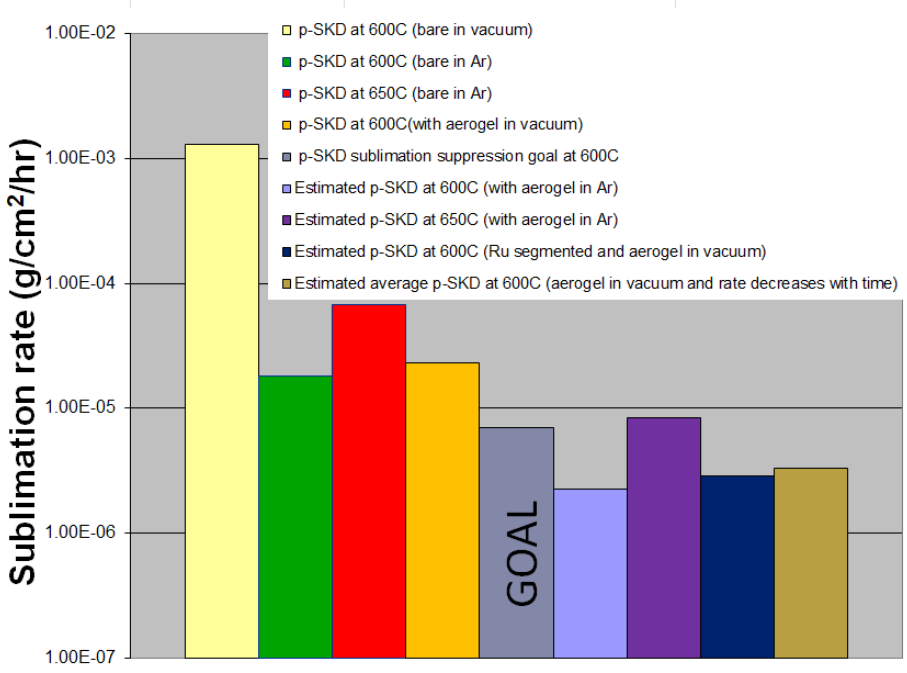


Initial JPL 2nd Iteration Couple (Gen. II) Testing : P/Po (normalized power) vs. time for P-legs

Several Couple Configurations Not Sensitive to both Sb Vapor and Diffusion Degradation Identified

Sublimation Rate for SKD Materials





- **Key findings**
  - Sublimation rate of p-SKD decreased by ~ 8 times with advanced insulation (aerogel)
  - Sublimation rate of both p and n-SKD in Ar decreased by ~ 100 times (compared with the values in vacuum)
- **Estimated sublimation rate with both Ar and aerogel**
  - p-SKD at 600C with Ar and aerogel: 2.2×10^{-6} g/cm^2/hr
  - n-SKD at 600C with Ar and aerogel: 2.6×10^{-7} g/cm^2/hr
- **Current sublimation rates are consistent with 17 years of operation**

Summary

- STM team successfully passed the gate 1
- JPL has transferred the processes for the fabrication of SKD materials, metallized elements, couples, and insulations to TESI
- TESI has developed manufacturing capabilities for SKD materials, metallized elements, couples, and insulations
- JPL and TESI retired the concern of 1st iteration couple life performance degradation due to oxidation
- JPL and TESI demonstrated manufacturing capability of 2nd iteration couples with good oxidation resilience
- The development of 2nd iteration (Gen. II) SKD couples with no or very limited Sb interaction is in progress

Acknowledgments

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

The authors would like to thank John Hamley, Radioisotope Power Systems (RPS) Program Manager and June Zakrajsek, RPS Programming, Planning, and Assessment Manager at the NASA Glenn Research Center (GRC) for supporting this work.